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LIFE CYCLE MANAGEMENT • SURVEY

A survey of life cycle approaches in waste management

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Abstract

Background, aim, and scope Life-cycle thinking and life-cycle approaches are concepts that are getting increased attention worldwide and in particular in EU Policies related to sustainability. The European Commission is launching a number of activities to strengthen life-cycle thinking in policy and business. EU policies aim to decrease waste generation through new waste prevention initiatives, better use of resources and shift to more sustainable consumption patterns. The approach to waste management is based on three principles: waste prevention, recycling and reuse and improving the final disposal and monitoring. In particular, concerning the prevention and recycling of waste, the definition of a waste hierarchy should be the basis for the prioritisation of waste management options. The benefit of using Life Cycle Assessment (LCA) in analysing waste management systems is the provision of a comprehensive view of the processes and impacts involved. However, it is also clear that the studies will always be open for criticism as they are simplifications of reality. Moreover, in order to become the LCA, a leading tool within businesses and government to understand and manage risks or opportunities related to waste management and treatment technologies, there are methodological choices required and a number of aspects that still need to be worked out. It is therefore important to review open and grey literatures, EU guidelines, relevant environmental indicators and databases for the waste sector and data easily usable in waste policy decision-making, with an agreed approach and methodology based on life-cycle thinking. The following survey gathers and describes the existing guidelines and methodologies based on life-cycle thinking and applicable in waste policy decision-making.

Main features This survey is focused on three main issues: definition and categorisation of waste streams and technologies; review and interpretation of existing waste-specific guidelines and tools; identification of specific key environmental performance indicators for the waste sector. Considering that a wide part of municipal solid waste is biodegradable and that their degradation is the main cause of greenhouse gas emissions in the waste management sector, considerable attention has been paid to biodegradable municipal waste.

Results The survey shows that general technical guidance documents should take into account the following key issues: how to categorise waste streams, how to develop a waste hierarchy from a life-cycle point of view, how to include any possible new waste treatment technologies and to take into account local and waste-related factors. Moreover, the survey summarises the generic/default values that could be used for waste-related key parameters when insufficient information/data are available. The survey identifies some key environmental performance indicators in the waste sector. The analysis of existing waste-specific guidelines and tools leads to a list of available methodologies and foreground/background environmental data sources that satisfy specific data constraints (origin, time-related coverage, geographical coverage, technology coverage).

Discussion The survey points out the need for strategic guidance documents for policy makers with quantitative examples to define the waste hierarchy. Depending on the characteristics of the specific cluster or area, such as climate, population density, etc., these documents should

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be integrated with quantitative considerations related to cost and social dimension, as complementary information to the environmental aspects of sustainability in waste management in order to address the preferable options to be considered for the definition of a local waste hierarchy.

Conclusions The survey shows that a considerable number of decision models and methodologies for the integration of life-cycle thinking into waste management have been developed for several waste streams and waste-management and treatment technologies. This leads to the need of a critical analysis of the existing guidelines and tools.

Perspectives A survey of life-cycle approaches in waste management has been presented in this paper. The analysis of specific waste streams and the integration of different environmental tools supporting the choice between different waste-treatment options could be taken into consideration for further work.

Keywords Biodegradable waste · Key environmental performance indicators (KEPIs) · Life-cycle approaches · Methodology · Tool · Waste · Waste hierarchy

1 Background, aim and scope

Life-cycle thinking and life-cycle approaches are concepts that are getting increased attention worldwide and in particular in EU policies related to sustainability. The European Commission is launching a number of activities to strengthen life-cycle thinking in policy and business: in 2001, the Commission adopted a Green Paper on Integrated Product Policy (IPP) (European Commission 2001), and in 2003 published its landmark communication on IPP (European Commission 2003a), with the objective of launching a debate on the role and possible measures that could be taken at European Union level in order to improve the environmental performance of products, services or product service systems throughout their life-cycles. In 2005, the European Commission further strengthened the role of life-cycle thinking in the Commission's Thematic Strategies programmed by the Sixth Environment Action Programme on the Sustainable Use of Natural Resources and on the Prevention and Recycling of Waste (European Commission 2005a, b, c). In 2008, finally, the Commission operationally launched the Sustainable Consumption and Production (SCP) Strategy by way of the publication of an Action Plan (European Commission 2008). As concerns EU waste-related policies, the European Commission emphasised the importance of waste minimisation, the protection of the environment and human health as priorities and advocated the waste hierarchy. Waste minimisation could be achieved through new waste-prevention initiatives, better use of resources and a shift to more sustainable consumption patterns. The approach to waste management is based on three principles: waste prevention, recycling and reuse and improving final disposal and monitoring. In particular, concerning the prevention and recycling of waste, a life-cycle perspective is considered essential by the EU for the sustainable management of wastes: life-cycle thinking can help reduce local pressures and waste management costs while considering the broader effects and trade-offs felt elsewhere across society. The European Commission's Directorate-General of the Joint Research Centre (DG JRC) conducted a series of life-cycle pilot studies in the context of municipal waste management (Koneczny et al. 2007). In this framework, the definition of a waste hierarchy should be the basis for the prioritisation of waste-management options. According to this hierarchy, that should be developed from a life-cycle point of view, recycling ranks higher than incineration with energy recovery, while landfilling ranks lowest. The waste hierarchy prioritises the prevention and reduction of waste, followed by reuse and recycling ending in waste disposal. The recycling is the highest-ranking waste treatment form as it ensures better exploitation of resources in waste (European Commission 1997). Although the waste hierarchy is a sound principle regarding the handling of some waste streams, waste hierarchy as a principle should be validated by using life-cycle assessment (LCA) and cost–benefit or cost-effectiveness methods (Schmidt et al. 2007).

The benefit of using LCA in analysing waste management systems is the provision of a comprehensive view of the processes and impacts involved. Environmental issues and opportunities can be addressed from a systems or holistic perspective. However, it is also clear that the studies will always be open for criticism as they are simplifications of the reality. Moreover, in order to adopt LCA in waste management, there are methodological choices required and a number of aspects that still need to be worked out (Finnveden et al. 2003). Issues such as upstream and downstream system boundaries, open-loop recycling allocation, multi-input allocation and time-frame should be considered when LCAs are applied to solid waste management systems (Clift et al. 2000; Finnveden 1999). Therefore, in order to be able to add up LCA-based information and to compare different waste strategies, common and harmonised calculation rules have to be used to ensure that similar procedures are used for data collection and handling (Finnveden 2000). An example of waste-specific LCA rules can be found in the Type III Environmental Declaration context (Del Borghi et al. 2007). It is therefore important to define guidelines, indicators and data easily accessible in waste policy decision-making, with an agreed approach and methodology based on life-cycle thinking and to test them in case-specific pilot studies covering the most representative polluting waste scenarios and treatment options.

As a large part of municipal solid waste (MSW) is biodegradable, considerable attention should be paid to specific guidelines and tools developed for biodegradable municipal waste (BMW). For the management of biodegradable waste that is diverted from landfills, there is no single environmentally best option. The environmental balance of the various options available for the management of BMW depends on a number of local factors, inter alia collection systems, waste composition and quality, climatic conditions, the potential of use of various waste derived products such as electricity, heat, methane-rich gas or compost. Therefore, strategies for BMW management should be determined with a life-cycle approach. The European Commission committed to produce guidelines on applying life-cycle thinking for the management of biodegradable waste. These guidelines will be communicated to EU Member States in order to revisit their own national strategies. These guidelines will also assist local and regional authorities that are generally responsible for drawing up plans for management of municipal waste (European Commission 2005a).

The following survey gathers and describes the existing guidelines and methodologies based on life-cycle approaches applicable in the waste policy decision-making.

2 Main features

This survey is focused on three main issues:

– Definition and categorisation of waste streams and technologies
– Review and interpretation of existing waste-specific guidelines and tools
– Identification of specific key environmental performance indicators (KEPIs)

An analysis and interpretation of waste differentiation criteria and hierarchy, of existing waste-specific guidelines and tools and of existing environmental performance indicators and optimisation models is performed in the following paragraphs.

As concerns waste differentiation criteria, waste can be categorised in many different ways: one way is to divide waste streams according to the sector generating it. Waste can also be divided into types or fractions. The different waste types are characterised by specific substance features or qualities which favour separate treatment because of economic, resource and environmental aspects (Danish Environmental Protection Agency 1999). For this differentiation, it is important to consider end-of-life characteristics such as recyclability. For example, in thermosetting resins, many hazardous volatile chemical compounds are used and may complicate the recycling process. Thermoplastic elastomers are not vulcanised, and thus, they can be easily recycled (IEC 2007). The survey analyses the common approaches for the definition and the categorisation of waste streams and technologies. In particular, the different waste management and treatment options are analysed basing on the definition of a waste hierarchy developed from a life-cycle point of view that leads to the identification of the following five main categories: recovery/recycle, biological treatment, thermal treatment, disposal in landfill and custom treatment (European Commission DG JRC 2008).

After a review of existing waste-specific guidelines and tools, environmental performance indicators for the waste sector, such as key environmental performance indicators, are identified. KEPIs can help to cut costs and the time required for studies by 90% or more, compared to the initial full studies, while achieving the same reliability (Pennington et al. 2007). KEPIs are a small number of product environmental performance indicators validated as representative of the most important environmental impacts of a life cycle. They provide a good and simple assessment tool for use in the waste sector. A full LCA study can be conducted after regular periods, and the KEPIs can be revised on the basis of the results obtained. KEPIs could possibly be used for simple assessment in the defining phase of waste strategies but may be more usefully applied in waste treatment technology decision-making. KEPIs are influenced by the decisions that are taken in the planning of the waste management system. Some KEPIs can be objectives for a decision maker (for example, minimisation of costs) or constraints to be respected (for example, the limits on low heating value). Moreover, they can be in contrast: achieving one target may mean to lose another objective. Thus, it is important to find a trade-off between the objectives and to calculate how much the KEPIs influence the decision alternatives (i.e., location and size of treatment facilities, recycling sizing, technology kind, logistics of collection, etc.) to be taken.

3 Results

3.1 Waste categorisation and waste hierarchy

In the European Union, the modern environmental protection policies and related legislation focus on preventing negative impacts on the environment that are the result of activities conducted by people. These nevertheless strive to do this also by banning the use of harmful substances, activities and procedures, the effects of which can cause permanent damage to the environment. The fundamental principle of environmental protection is thus prevention. For enforcing this principle, basic information must be provided on the basis of which certain measures can be

adopted. Data on the amount of waste generated and waste management are also very important for proper policy-making. For the data to be relevant and correct, it is, of course, necessary to implement accurate data collection, processing and analysis, which are provided by statistical surveys in these fields. However, these surveys need to be harmonised with the legislation governing the field of waste in individual countries as well as in the European Union.

Some authors have attempted to show individual waste streams, statistical collection of these data, their processing and requirements (Zitnik 2005). The European Union Waste Statistics Regulations (European Commission 2002) requires all Member States to provide data to the European Commission every 2 years on the generation and treatment of waste and on the number and capacities of waste management facilities. The aim of the regulations is to establish a European-wide database on waste generation and treatment so that, for example, waste policies and legislation can be better monitored and evaluated. Eurostat, the Statistical Office of the European Communities, compiles the data to provide statistics at European level. Therefore, available data concerning waste generation (quality and quantity) and management (recovery/recycle; treatment; disposal) could be taken from statistical collection data (i.e. Eurostat 2000, 2008; den Boer et al. 2007). In particular, the last Eurostat publication based on the data collection via the joint Organisation for Economic Cooperation and Development (OECD)/Eurostat questionnaire, replaced in 2006 by reporting under the Waste Statistics Regulation, provides important baseline data for the implementation of National and European policies on waste management (European Commission 2005b).

The European Commission has defined several specific waste streams for priority attention, with the aim of reducing their overall environmental impact. This includes packaging waste, end-of-life vehicles, batteries and electrical and electronic waste. EU directives now require Member States to introduce legislation on waste collection, reuse, recycling and disposal of these waste streams. A large discrepancy among EU countries and regions in the implementation of waste policy could be observed. For instance, in the northern EU countries, on average 20% of waste was collected separately, while in the southern only 5%. Some EU members (e.g. Germany) achieved higher recovery and recycling rates for packaging wastes than target values, while other countries, such as Portugal, Greece, France and Spain, appeared not to be making as much progress (den Boer et al. 2007). Therefore, for a correct waste categorisation, the identification of European representative areas/clusters of waste distribution, production and management and the identification of the main sectors generating wastes seem to be necessary. In order to define a specific set of rules for the application of life-cycle tools (such as LCA and Design for Environment) to waste management, waste could be further differentiated at least in the following types or fractions: BMW, greenwaste, wood, textiles, glass, paper and cardboard, plastics (thermoplastic, thermosetting polymers), metals, batteries and waste electrical and electronic equipment.

Once wastes have been categorised, a waste hierarchy could be developed in order to describe, in a life-cycle point of view, a preferential order of different options to deal with solid waste: waste prevention, material recycling, energy recovery and final disposal. However, this hierarchy can be seen as a helpful and valuable general guidance rather than a concrete tool to identify the best waste management option.

Since 1994, the US Environmental Protection Agency (EPA) has worked to apply life-cycle concepts and tools to the analysis of MSW management systems in the USA (Thorneloe et al. 2007). Over the last few decades, the waste hierarchy has been the guiding principle also in the European waste management policy. Since its launch, the goal has been to reduce the total quantities of waste and to save energy and resources. In particular, the Danish environmental authorities have followed a strategy very similar to the one used in the European Union (Schmidt et al. 2007), considering the waste hierarchy as a guiding principle which can clearly be seen in the goals formulated in official policies. In the Danish waste-strategy ‘Waste 21’ action plan (Miljø-og Energiministeriet 1999), objectives for increased recycling of paper, organic waste from households and a priority for using the Danish system of reusing bottles have been set. In the newly launched action plan “Waste Strategy 2005–2008” (Miljøministeriet 2003), there is more emphasis on the use of waste indicators and cost–benefit analysis.

The German Closed Substance Cycle and Waste Management Act from 1994 (Ministry for the Environment, Nature Conservation and Nuclear Safety 1994) provides several examples on how the environmental objectives can be described whilst maintaining flexibility in how to best achieve them: this ensures that the environmentally preferable waste management solution can be followed.

The Waste Strategy for England 2007 highlights that “Recent studies have confirmed that the waste hierarchy remains a good general guide to the relative environmental benefits of different waste management options, but that there will be exceptions to this for particular materials and in particular circumstances. The use of the waste hierarchy should be informed by life-cycle thinking and the broader SCP agenda” (UK DEFRA 2007).

3.2 Life-cycle assessment models for waste management

During the early 1990s, scientists began developing general models to conduct life-cycle assessments for waste man-

agement systems. A selection of six different models developed in Europe and America by research organisations, industry associations and governmental institutions and their comparison have been performed by Winkler and Bilitewski (2007). Instead of starting from scratch for each case study, the models provide the most important waste management and treatment technologies, such as:

- Recovery/recycle technologies of the considered waste streams
- Biological treatment: composting, anaerobic digestion (differentiation will be done by technologies: aerobic, anaerobic, open/close, static/dynamic, aerated/not aerated) and biofuels synthesis.
- Thermal treatment: incineration/co-combustion, gasification/pyrolysis. Current facilities and directive compliant plant with energy recovery will be differentiated (no differentiation will be done by air treatment technologies).
- Disposal in landfill: directive compliant, methane capture. Different-treatment technologies and leachate treatment methods could be included.
- Custom treatment defined by the users: combination of the default treatments

A description of the existing models (guidelines and tools) developed for above-mentioned technologies and for Waste Collection and Mechanical Biological Pre-Treatment, that could be part of each of them, is provided in Table 1.

The purpose of developing these models was not only to speed up the analysis but to promote life-cycle approaches in waste management. The models enabled decision makers and waste managers to conduct life-cycle assessments for their specific waste management system without in-depth knowledge of the methodology and allowed them to learn how changes in the system affect the environmental impacts through scenario analysis.

Concerning waste-related guidelines, the PCR 2008:02 ‘Solid Waste Disposal’ (PCR 2008:2 2008; Del Borghi et al. 2007) could be a useful support for methodological choices (functional unit, system boundaries, data quality, impact categories) performing LCA studies in waste sector. In fact, Product-Specific Requirements (PCRs) are common and harmonised calculation rules established in the framework of The International EPD® System, an application of ISO 14025:2006, to ensure that similar procedures are used when creating an Environmental Product Declaration.

As concerns specific guidelines and tools developed for biodegradable waste, the DG JRC performed several studies on the organic fraction of municipal solid waste. The JRC's invited expert meeting on life-cycle assessment of treatment options of biodegradable waste (Koneczny et al. 2007) includes a review of the commonalities and differences of LCA studies in the context of policies and strategies at national or sub-national levels with the aim of providing potential recommendations to further develop commonly agreed European policies. Moreover, the DG JRC published the life-cycle guidelines for the management of the organic fraction of municipal waste (European Commission DG JRC 2008). The connected excel tool is a decision model consisting of three levels of decision making: the proposed methodology can be a valid approach, while the treatment methods could be expanded to take into account additional methods. Life cycle inventory (LCI) data derive from reference technologies for the most common biodegradable waste products, treatments and collection methods, taken from the Dutch Waste Management Plan 2002-2012 (AOO 2002).

The European communication SEC (2005) 1681 (European Commission 2005c) outlines the strategic approach on the prevention and recycling of waste and indicates how to proceed with its implementation. The proposal for revision of the Waste Framework Directive and other pieces of legislation proposed together with the communication are the first measures implementing the strategy. It includes interesting consideration on environmental and economic impacts of options for recycling and recovering waste and a simplified model for the evaluation of current and potential climate change impact of waste policy. The study launched by the European Commission DG-ENV and carried out by COWI A/S (2004) aims to assess the main social, economic and environmental implications of a selected set of policy for better and/or increased biological treatment of biodegradable waste. It includes an assessment of three EU representative countries (Portugal, Ireland and Sweden) and an extensive literature review as well as targeted collection of data and information.

The Nordic Council of Ministers developed a computer-based decision tool for Nordic municipalities with a wish to evaluate environmental consequences of systems for collection and treatment of the organic fraction of MSW. The proposed methodology can be a valid approach, while data should be updated from a local perspective (Nordic conditions) to a European level (Nordic Council of Ministers 2007). Moreover, the NORDTEST published a report (Bjarnadóttir et al. 2002) containing LCI data and guidelines to the application of life-cycle assessment in the waste management sector. Focus is put on the most common municipal waste management scenarios in the Nordic countries, and the guidelines are supported with case studies in the appendices. It could be a useful support for methodological choices and LCI data sources.

3.3 Waste data quality

As described, waste treatment is a complex chain of processes, and the structure of the chain depends on the

Table 1 Models for waste management and treatment technologies

Technologies	Description	Sources
Waste collection Source-separated collection Not source-separated (mixed urban waste) collection	Waste collection represents one of the most polluting phase of the life cycle of waste management. Specific data should be used for amounts of inputs and outputs in following activities: (a) waste transport (fuel use and emissions in conjunction with transportation); (b) distances of transportation within the municipalities and to the waste treatment plant and type of vehicles. Typical fuel consumptions for waste collection (traditional and separated) in different types of residential areas are reported in the Nordic Council's study. The separate waste collection performance in European cities was analysed in the FP5 Research Project LCA-IWM	Nordic Council of Ministers (2007) LCA-IWM (2005)
Mechanical biological pre-treatment		
Pre-Treatment of rest waste after separate collection (or mixed urban waste) Pre-treatment technologies: default/disc screen/hydraulic screw press for dry-wet separation Aerobic/anaerobic treatment of the wet fraction of waste	Mechanical biological pre-treatment (MBP) represents a key phase of residual/mixed waste treatment. The MBP consists of mechanical pre-treatment with separation of the high caloric light fraction and biological treatment of the remaining waste prior to landfilling (the so-called 'splitting' approach). The biological process in the aerobic MBP is conducted in an aerated windrow with a weekly turning of the material. In the anaerobic MBP, the biological process consists of a fermentation stage producing biogas. Both Nordic Council's tool and the LCA-IWM tool includes LCI data on MBP	Nordic Council of Ministers (2007) LCA-IWM (2005)
Recovery/recycle technologies		
Material recovery Waste collection Recovery/recycling plant Final disposal	Material recovery consists of waste collection, the material recovery plant, transport of the recycling materials to the remanufactures and the final disposal for the non-recyclable residual waste. Recovered materials from wastes that are reprocessed can be used to replace virgin materials, and this may result in overall savings in raw materials and energy consumption and emissions to air, water and soil. The models described by Winkler allocate the savings from the remanufacture of recycled materials to the waste management system. The LCA-IWM tool includes LCI data on the main and most common manufacturing and recycling processes for the following different waste streams: paper and cardboard, glass, metals (ferrous and non-ferrous), plastics and composites and Waste Electrical and Electronic Equipment. For all the above mentioned waste streams, "environmental crediting modules" are defined to allow balancing the environmental advantages and disadvantages of materials recycling processes against virgin materials production processes	Winkler and Bilitewski (2007) LCA-IWM (2005)
Biological treatment		
Composting Default composting plant Open/closed reactor Aerated/not aerated Static/dynamic Maturing process in windrow Home composting	Composting represents, together with anaerobic digestion, one of the most common technologies for biodegradable waste treatment. It is the preferable treatment of material of good structure (wood-like, celluloses). It could be used for: stabilisation of the wet fraction of waste before landfilling (see aerobic treatment of the wet fraction of waste); treatment of source separated waste from households, gardens and industry; greenwaste composting. The LCA-IWM tool describes the composting process in a two-step technology: (1) intensive composting in composting boxes and (2) maturing process in windrows in a composting hall. The Nordic Council's tool includes: windrow, closed reactor, home composting. Different composting technologies and phases could be analysed. Process air can be treated in a biofilter. The produced compost can be applied to agricultural soil, thus substituting artificial fertilisers and peat	Nordic Council of Ministers (2007) LCA-IWM (2005)
Anaerobic digestion Default biogas plant (mesophilic/thermophilic conditions) BTA® (Biotechnische Abfallverwertung) Waste Pulper (mechanical pre-treatment and biological conversion)	Anaerobic digestion represents, together with composting, one of the most common technologies for biodegradable waste treatment. This treatment causes the degradation of organic matter and the separation of the waste in gas and in different residual fractions. In the digestion plant, both BMW and garden waste are allowed waste inputs. Both traditional and innovative technologies can be included. Anaerobic digestion leads to methane production that can be utilised for energy production. Both Nordic Council's tool and the LCA-IWM tool include LCI data on specific technologies of anaerobic digestion	Nordic Council of Ministers (2007) LCA-IWM (2005)

Combined treatment with municipal wastewater in a Wastewater Treatment Plant (WWTP)		
Biofuels synthesis	New methods of organic wastes treatment that allow a more complete and efficient conversion of the wastes are needed. One of the most common method that produce a higher value product than current methods is the production of alcohol, and in particular ethanol, from biodegradable waste. In this method, organic material is first fermented by anaerobic microorganisms to a biogas consisting primarily of methane and carbon dioxide. The biogas is then converted to synthesis gas consisting primarily of CO and H_2. The syngas is then contacted with a catalyst that catalyses the condensation of CO and H_2 to form alcohol-typically mixed alcohols consisting primarily of ethanol. Moreover alcohol could be produced directly by fermentation of biological residues through biotechnological processes	US Patent
Alcohol production from the organic fraction of waste		Perego et al. (2000)
Thermal treatment		
Incineration/co-combustion of residual fraction of waste	Both primary (collected residual/mixed household waste) and secondary (output from MBP and residuals from recycling and treatment plants) waste streams can be directed to the incinerator or to the final disposal option: the landfill. Moreover residual waste can be co-combusted e.g. in cement plants. Both Nordic Council and LCA-IWM tools include LCI data on Incineration. The Nordic Council's tool includes: CHP, heat plant, default incineration. The LCA-IWM tool includes only the CHP plant. The incineration technology should be chosen among the Best Available Technologies (BAT). No differentiation will be done by air treatment technologies	Nordic Council of Ministers (2007)
Current facilities		
Directive compliant incineration with energy recovery, combined heat and power (CHP)		LCA-IWM (2005)
Co-combustion in cement plants		
Gasification/pyrolysis of residual fraction of waste	These advanced thermal treatment are not as widely applied to waste treatment. In these technologies, oxygen (air) is either not supplied (pyrolysis), or is restricted below the quantity required for full oxidation of the waste (gasification). Both systems generally result in the production of a gas, which may be used as a fuel or a chemical product. In general they are coupled with a subsequent combustion stage from which the thermal and/or electrical energy may be recovered. These treatments may well be more suitable for treating the Refuse Derived Fuel products produced by mechanical biological treatment processes rather than processing residual household waste. BAT data could be used	European Commission IPPC (2006)
Disposal in landfill		
Landfill	The landfill, as the final disposal option, should be a modern plant at which waste is disposed of. Input waste includes MSW, MBP waste and residues from waste treatment facilities. According to the relevant PCR 2008:02, biogas and leachate production should be modelled for 30 years after landfill closure. Different pre-treatment technologies and leachate treatment methods could be included. The collected gas can either be utilised for energy production or alternatively be burned in a flare. Both Nordic Council and LCA-IWM tools includes LCI data on landfill	PCR 2008:02 (2008)
Directive compliant		
Methane capture: combustion in a flare/engine		Nordic Council of Ministers (2007)
Different pre-treatment technologies (organic treatment, biocells)		LCA-IWM (2005)
Different leachate treatment methods (together with municipal wastewater, chemical-physical, reverse osmosis)		
Custom Treatment	Various technically feasible combinations of the default treatments could be analysed	

Table 2 Foreground data sources

Foreground Data Sources	Publisher/Editor	Time	EU	Tech.	Note	Sources
DG JRC "Life cycle guidelines for the management of the organic fraction of municipal waste (biowaste)" excel tool (2008) and experts comments	JRC-IES, EU	2002	X	X	It is an excel tool consisting of three levels of decision making: Level I: Applying general rules; Level II: Applying the life-cycle reversed approach; Level III: Performing a detailed LCA study. The following waste treatment processes have been modelled: gasification, digestion, composting, incineration, landfill. LCI data derives from reference technologies, taken from the Dutch Waste Management Plan 2002–2012 for the most common biodegradable waste products, treatments and collection methods.	AOO (2002)
ELCD database "European Reference Life Cycle Data System"	JRC-IES, EU	2007	X	X	It is a high quality LCI core data sets of the first version of the Commission's "European Reference Life Cycle Data System" (ELCD), v 1.0.1. The database comprises—next to other sources—LCI data sets of end-of-life treatment (energy recycling, disposal) and transport services. All these data sets are officially provided and approved by the named associations for publication in the Commission's ELCD core database.	European Commission DG JRC (2007)
LCA-IWM Assessment Tool FP5 Research Project "The Use of Life-Cycle Assessment Tool for the Development of Integrated Waste Management Strategies for Cities and Regions with Rapid Growing Economies"	Research Project, EU	2002–2005	X	X	The LCA-IWM Assessment Tool (Integrated Waste Management) is an excel interface programmed with Visual Basic for Applications (VBA). It allows modelling of waste management scenarios at a municipality level. The following waste treatment processes have been modelled: composting of separately collected organic waste; digestion of separately collected organic waste; aerobic/anaerobic mechanical-biological pre-treatment of mixed/residual waste; incineration with energy recovery of mixed/residual waste; recycling of separately collected materials; landfilling of mixed/residual waste. The LCA-IWM Waste Prognostic Tool is an estimation tool for the future generation of municipal solid waste in European cities.	LCA-IWM (2005)
Nordic Council's tool	Nordic Council of Ministers	2007	–	X	It is an excel decision tool for Nordic municipalities. The following waste treatment processes have been modelled: waste collection; pre-treatment; composting; anaerobic digestion; combined digestion and composting; use on land; incineration. Data are representative of the Nordic conditions.	Nordic Council of Ministers (2007)
WRATE (Waste and Resources Assessment Tool for the Environment)	Env. Agency of Wales, UK	2002–2009	–	X	The tool contains a foreground database of 140 waste processes covering: home composting, waste collection (containers, sacks and vehicles) and transport (waste vehicles and private vehicles), waste transfer, pre-treatment and sorting (civic amenities, material recycling facilities (MRFs), mechanical biological treatment, waste treatment and recovery (composting, incineration with energy recovery, anaerobic digestion/bioethanol, advanced thermal treatments), materials recycling and disposal (incineration without energy recovery and landfill). WRATE	www.wrate-LCA.co.uk

					supersedes the previous life-cycle tool WISARD as it incorporates a greater range of waste management technologies. ‘Foreground’ waste management process data is representative of current and future UK waste management systems. The data is sourced from the UK operating and pilot plants or from European or other international plants where UK data is not available.	
ORWARE (ORganic WAste REsearch, Sweden) (SLU, IVL, JTI, KTH)	Research Institutes SE	1993–2002	–	X	It is a Matlab/Simulink substance-flow simulation model. There are 9 submodels: incineration; wastewater treatment; anaerobic digestion; composting; landfill; waste collection; truck transport; wastewater transport in sewers; spreading of waste products on agricultural land. Data are representative of the Swedish conditions.	www.ima.kth.se/im/orware/
EASEWASTE (Environmental Assessment of Solid Waste Systems and Technologies, Denmark)	University, DK	2006	–	X	It is a model for environmental assessment of waste systems developed by the Technical University of Denmark. The model considers environmental impacts from waste generation, collection, treatment and disposal, including a submodel for assessment of environmental impacts from land application of treated organic waste. The sub-model builds largely on specific emission coefficients derived from field experiments and simulations. The inherent default data are based on ‘typical Danish scenarios’, but data for different conditions can be entered.	www.easewaste.dk
WISARD (Waste-Integrated Systems Assessment for Recovery and Disposal)	Env. Agency, UK	1999	–	X	The tool includes the data on waste management operations and processes compiled under the Agencys programme, as well as background data on raw materials, energy and other processes in life cycle from Ecobalance UKs (The Ecobilan Group) proprietary life-cycle database	www.ecobalance.com/uk_wisard.php
IWM2—Integrated Waste Management 2—Procter & Gamble (UK)	Industry, UK	1999	–	X	It is a LCI model (SQL, Structured Query Language, Database) that allows the prediction of the overall environmental burdens and economic costs of municipal waste management. It is designed to be an “entry level” LCI model for solid waste and appropriate to users starting to apply lifecycle thinking to waste systems. Among sections of waste management that are treated in the model there are waste collection, sorting, biological treatment, thermal treatment, landfilling and materials recycling.	McDougall (2001)
Decision Support Tool (DST)	Env. Agency (US EPA)	2000	–	X	It is a LCI excel/CPLEX tool to evaluate integrated municipal solid waste strategies in the United States with respect to environmental and economic impacts. The tool includes waste collection, transfer stations, recovery, compost, incineration and landfill as well as several additional external unit processes (e.g. data from electricity production). Through an optimisation module the user can identify objectives as minimising total cost or life-cycle parameters such as energy consumption and greenhouse gases. Data are representative of the North America conditions.	https://webdstmsw.rti.org Thorneloe et al. (2007)
I-LCA Version 2 (2000)	Env. Agency, IT	2000	–	X	It is a LCI tool containing a foreground database of 173 waste processes including waste collection, selection, biological treatment, incineration, landfill for 22 municipal waste groups. LCI data have not been updated. It includes the methodology ‘SMAR Model’, an excel based support tool for integrated waste modelling.	Baldo and Pretato (2001)

waste source, country, waste treatment, transportation, etc. Providing a simple guideline regarding the data availability and quality for the waste sector is difficult. There are a variety of good publications and case studies from different countries available on the web pages of EPA, Energy Regulators Regional Association and EU. Also, a lot of good information can be found in the proceedings of the international workshop organised on LCA and treatment of solid waste (AFR-report 98 1998) and in the SETAC-Europe LCA Working Group Data Availability and Data Quality (Braam et al. 2001). The DG JRC has produced the ELCD database (European Commission DG JRC 2007) that comprises LCI data from front-running EU-level business associations and other sources for key materials, energy carriers, transport, and waste management. The respective data sets are officially provided and approved by the named industry associations.

Concerning data quality, some authors (Weidema and Wesnaes 1996) suggest to derive a generic list of criteria for a data quality assessment from recently published articles:

- Statistical representativeness of data
- Age of data
- Data collection method
- Quantitative analysis of flows
- Processes that are taken into account
- Aggregation level for flows
- Mass balance
- Geographical representativeness
- Temporal representativeness
- Technological representativeness
- Functional unit definition
- Allocation rules
- Uncertainty intervals specified

Generic/default values for waste-related key parameters, when sufficient information/data are not available, are presented in Table 2. The foreground and background data sources that satisfy data-specific quality constraints are shown in Tables 3 and 4: temporal representativeness (Time), geographical representativeness—European (EU) or International (Int.) and technological representativeness (Tech.) are assessed for the considered data sources.

3.4 KEPIs in the waste sector

KEPIs are product environmental performance indicators. They are representative of the most important environmental impacts of a life cycle and could be considered a simple approach for conducting environmental assessments. KEPIs do not always replace detailed studies, in particular, if detail assessments are required for new technology or new process, and a peer review body and agreed timescale for periodic re-validation of KEPIs is required. However, these indicators

Table 3 Background data sources

Material	Background Data Sources	Origin	Time	EU	Int.	Tech.	Note
Aluminium	EAA (European Aluminium Association)	Industry Association	2008 (based on study of 2005)	X	–	X	Suggested by PCR 2008:02
Building materials and products	BEES (Building for Environmental and Economic Sustainability) ATHENA® Impact Estimator for buildings	Industry	2007	–	X	X	Suggested by PCR 2008:02
Electricity	Data combined with IEA (International Energy Agency) statistics on electricity generation mixes for nations, regions etc.	Industry Association	2008	X	–	X	Suggested by PCR 2008:02
Fuels	ELCD database	Industry	2002–2003	X	X	X	European representativeness
Plastics, Chemicals	PE Plastics Europe (former APME Association of Plastics Manufacturers in Europe)	Industry Association	2004	X	–	X	Suggested by PCR 2008:02
Primary copper	ICA (International Copper Association)	Industry Association	2004	X	X	X	Suggested by PCR 2008:02
Copper products	ECI (European Copper Institute – Life Cycle Center)		2005				
Steel	IISI (International Iron and Steel Institute)	Industry Association	2000, 2008	–	X	X	Suggested by PCR 2008:02
Transports	ELCD Database	Industry	2007	X	–	X	European representativeness
	NTM (Network for Transport and Environment) or regional alternatives						Suggested by PCR 2008:02

Table 4 Generic/default values for waste-related parameters

Parameter	Generic/Default Values	Sources
Waste composition	Annex V of 'Municipal waste management and greenhouse gases' ETC/RWM working paper. Data acquired from the NIR (National Inventory Report) and CRF (Common Reporting Format) reports to UNFCCC and corrected using OECD (2001) data. (http://waste.eionet.europa.eu/publications/wp2008_1/wp/wp1_2008)	ETC/RWM 2008/1
Logistic	Average distances of transportation within the municipalities (30 km) and from the transfer station to the waste treatment plant (50 km); type of vehicles (truck 20 t). For biodegradable waste the stop and go route is estimated at 5 km on average. The distance from the collection area to the transfer station is estimated on average 10 km. Average distances have been calculated for the Dutch situation. It is therefore advised to use actual distances if available. These data strongly depend on the availability of the treatment facilities	AOO 2002
Biogas production	200 m^3 from 1 t of municipal solid waste (for 30 years)	PCR 2008:02
Biogas composition	50% CH_4; 50% CO_2 (v/v)	PCR 2008:02
Biogas collection	60% biogas collected, 40% biogas lost	PCR 2008:02
Energy Feedstock	10 MJ for 1 kg of municipal solid waste	PCR 2008:02
Leachate production (for a Mediterranean Climatic Zone)	150 l from 1 t of municipal solid waste (for 30 years) This common value has to be used with particular care as leachate production is very variable and depends on different parameters	PCR 2008:02
Quantity of dry matter (DM) for biodegradable waste	As default: kitchen and soft garden waste 40% DM (Dry Matter) content, hard garden waste 59% DM content	AOO 2002
Electricity from Syngas (CO, from gasification)	912.5 kWh el. per ton DM	AOO 2002
Biogas (CH_4, from anaerobic digestion)	531.5 kWh per ton DM (revised version of the dataset used in AOO 2002)	AOO 2002
Compost or digestate not meeting national standards (heavy metals) for landfill	Average is 0.88 ton compost per ton DM	AOO 2002
Electricity from waste incinerator	444.25 kWh el. per ton DM at a 20% energy efficiency	AOO 2002
Heat (when avoiding heat production)	666.25 kWh th per ton DM at a 30% energy efficiency	AOO 2002

are easy to communicate internally and externally and easy to use and understandable to a non-technical reader and could be used to compare different waste management strategies in a preliminary decision making phase.

In the waste sector, specific indicators, such as efficiency of dry–wet waste separation, organic waste stabilisation efficiency, energy recovery, production of by-products, could be use to characterise any possible new waste treatment technologies. A preliminary KEPIs list should take into consideration at least the following indicators: economic costs, unrecycled waste, sanitary landfill disposal and environmental impact (emissions to air, water and land). Concerning local and waste-related factors, the following indicators could be used: local legislation, existing management infrastructure, collection systems availability, waste composition and quality, climatic and geographic conditions, population density and population behaviour, the potential of use of electricity and/or heat and/or biogas or other by-products and the potential of compost to contribute to local soil improvement. A list of indicators that could be applied in the waste sector is presented in Table 5.

The necessity of using a multi-objective framework to consider the MSW management problems arises from the difficulty of finding simple trade-offs between economic and environmental objectives. A realistic model of the decision process has to take into account the interactive features that generally characterise the process. This interaction takes place whenever the decision makers have to evaluate a certain solution and then express their preference trade-offs. The difficulty lies in correctly involving the decision makers (not necessarily a technician) and possibly iteratively interacting with them. To find a balance between the objectives and to calculate how much the KEPIs influence the decision alternatives to be taken, an approach based on optimisation has been proposed by several authors (Minciardi et al. 2008). Tsiliyannis (1999) discusses the major environmental problems related to MSW management, in particular those concerning pollutant release. Solano et al. (2002) describe a linear optimisation

Table 5 Examples of KEPIs in the waste sector

KEPIs	Description
Waste composition (organic matter—total organic carbon (TOC), dissolved organic carbon (DOC), hazardous content). Dry matter (DM) for biodegradable waste	Compliance with Landfill Council Decision 2003/33/E (European Commission 2003b) that includes very strict limits as regards organic matter and hazardous content
Calorific value	Compliance with Directive 1999/31/EC and with national acknowledgments including limits as regards Low Heating Value (LHV)
Time horizon for plant management	It influences treatment costs (i.e. landfill)
Energy recovery Material recovery and recycling	It highlights the recovered material/energy and the type of avoided products
Emissions to air, water and land	It is an indication of the negative impacts of the waste management system
Total costs	It states if the waste management is economically sustainable through an economic balance and an analysis of market opportunities
Waste to landfill (or saturation time for landfill)	It is an indication of how much is not recovered by waste and its environmental impact
Feasibility/Availability of treatment facilities Transport requirements/costs Type of collection method Mode of transportation (e.g. type and/or size) Frequency of waste fractions collection Distance to waste transfer station	Transports (due to more complex collection scheme, longer distance to specialised treatment plants, economic reasons) reduce the ecological benefit of recycling: the break-even-point should be identified for each waste stream

model for integrated solid waste management intended to help in identifying alternative strategies that meet cost, energy and environmental emission objectives. Costi et al. (2004) propose a decision-making strategy that takes into account the environmental impact of MSW by introducing suitable constraints into the decision model. Solid waste management is obviously a complex problem involving several components, among which social components and community participation are key factors in decision making (Srivastava et al. 2005; Joos et al. 1999; Hung et al. 2007). Among the best suitable methodologies to deal with multi-objective problems within the management of environmental systems is the so-called reference point method (Wierzbicki et al. 2000), as it consists of decision processes where decision makers are progressively asked to express their preferences. In these models, relations between KEPIs and alternatives (decision variables) are mathematically formalised and represent objective functions and/or constraints of the optimisation problem. Standard optimisation tools are used to find the optimal values of the objective functions, the decision variables and other performance indexes of interest. Then, a sensitivity analysis can be performed on the optimisation problem: relaxing or restricting the importance of a specific performance indicator, it is possible to verify how the optimal solution and the performance indicators vary. In this way, it is also possible to identify KEPIs that are most important and KEPIs that do not influence the decision alternatives.

4 Discussion

The survey points out the need of strategic guidance documents for policy makers with quantitative examples to define the waste hierarchy. As one specific waste treatment is often not sufficient, the examples to be used should include also the interpretation of the different treatment process to be considered, depending on the different local situations. A strategic guidance to be used in the waste sector should be integrated with quantitative considerations related to safety, cost and social dimension, as complementary information to the environmental aspects of sustainability in waste management. Depending on the characteristics of the specific cluster or area, such as climate, population density, etc… strategic guidance documents should address the preferable options to be considered in order to define a local waste hierarchy.

For this purpose, a valid support could be represented by the recent definition of the PCR 2008:02 ‘Solid Waste Disposal’ (PCR 2008:2 2008) that include specific requirements for all the possible treatments applicable to solid waste, including several end-of-life scenario for waste generated itself, in order to make more easily comparable the results of different LCA studies on waste management than in the past. Referring to this PCR, several comparative LCA studies could be performed for each specific category and/or for a specific type of treatment, in order to define what type of process has the lowest impact and the best

environmental performance. At the same time, considering the application of recovery/recycle technologies, specific conditions should be defined to determine if and when recovery/recycle is preferable to a conventional disposal, in terms of environmental global impacts.

5 Conclusions

In this paper, a survey of life-cycle approaches in waste management is presented together with the results of a critical analysis of the following issues: definition and categorisation of waste streams and technologies; review and interpretation of existing waste-specific guidelines and tools; identification of specific key environmental performance indicators for the waste sector.

The definition and categorisation of waste streams and technologies represent the first step in the development of a waste hierarchy, used for the prioritisation of waste management options at European and international level. Data concerning waste distribution, generation (quality and quantity) and management (recovery/recycle; treatment; disposal) and the identification of the main sectors generating wastes could be taken from statistical collection data, such as the last Eurostat publications. Although the waste hierarchy is a sound principle regarding the handling of some waste streams, waste hierarchy as a principle should be validated by introducing life-cycle approaches in waste management.

For this purpose, a considerable number of decision models and methodologies have been developed for several waste streams and waste management and treatment technologies. These models enable decision makers and waste managers to use life-cycle assessments for their specific waste management system without in-depth knowledge of the methodology. In the paper, an analysis of specific guidelines and tools differentiated for the most important waste management and treatment technologies is presented. The analysis shows that most of the existing guidelines and tools have been developed by North European countries through EU-funded projects. As data availability and quality represent a crucial issue for a proper use of these models, a list of generic/default values for waste-related key parameters and of foreground and background environmental data sources is provided.

In the paper, the use of product environmental performance indicators such as KEPIs in the waste sector is assessed. The survey shows that KEPIs and optimisation models are easy to use and understandable to a non-technical reader and could be used to compare different waste management strategies in a preliminary decision-making phase; nevertheless, they cannot replace detailed LCA studies. A list and a description of indicators that can be used in the waste sector is presented.

6 Perspectives

The survey presented in this paper has been focused on life-cycle approaches in waste management described through an analysis of the existing guidelines and methodologies based on life-cycle thinking and applicable in waste policy decision-making.

The main outcomes of this survey show that there is a strong need of a single reference document, easy understandable to a non-technical reader, to be used as a guideline in the waste sector. Therefore, a subsequent step of research could be focused on the analysis of specific waste streams management and treatment technologies and on the integration of different environmental tools supporting the choice between different waste treatment options. For example, widely applicable instrument assisting in the decision making process (planning, decision making and post-decision making surveillance), such as the Environmental Impact Assessment (EIA) and the Strategic Environmental Assessment could be profitably integrated with life-cycle approaches in order to take into account all relevant effects, which may be crucial for a proper comparison of alternatives. Particularly in strategic and project EIAs, environmental comparisons of process and abatement alternatives may be relevant. Although these alternatives may lead to different emissions and effects at the location of the process itself (which is usually the focus in project EIAs), they can also influence the demand for activities upstream and downstream in the production chain, highlighting the necessity of considering all life-cycle phases.

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